VLBI SURVEY OF A COMPLETE SAMPLE OF ACTIVE NUCLEI AND QUASARS +

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ABSTRACT

We have conducted a VLBI survey of a complete, flux-density limited sample of 65 extragalactic radio sources, selected at 5 GHz. We have made hybrid maps at 5 GHz of all of the sources accessible to the Mark-II system. The sources can be divided provisionally into a number of classes with different properties: central components of extended double sources, steep-spectrum compact sources, very compact (almost unresolved) sources, asymmetric sources (sometimes called "core-jet" sources), and "compact double" sources. It is not yet clear whether any of these classes is physically distinct from the others, or whether there is a continuous range of properties.

1. INTRODUCTION

Since 1977 we have been engaged on a project to determine the structure of a complete, unbiased sample of VLBI sources, and to measure changes in the sources. The sample consists of 65 sources, of which 45 have VLBI structure. Mapping 45 sources with our present instrumentation is a very large project, but even so, 45 is a small number for statistical studies. Thus, although statistical trends may become apparent, our purpose is more to provide an overview of the range of morphologies exhibited by the sources.

We cannot overemphasize the importance of studying a complete sample of this type. There has been a tendency in VLBI to concentrate on a small number of sources of special interest, such as the superluminal sources, simply because VLBI is still very time-consuming; although things are getting easier these days with the establishment of the U.S. and European VLBI Networks. Studies of individual sources can, of course, be very rewarding, but they leave many questions unanswered, and may even bias our view of the VLBI universe. In addition to exploring the menagerie of source morphologies, we can address a number of specific questions by way of a complete survey, all

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aimed ultimately at elucidating the fundamental cause of galactic nuclear activity. For example, we may expect to find more superluminal sources, and find out just how common they are - an important parameter for the relativistic-beaming theories; and we can look for correlations between VLBI and optical and X-ray properties of the sources which may indicate physical connections and constrain theoretical models.

2. THE COMPLETE SAMPLE

The sample we have chosen to study contains 65 sources, selected from the NRAO-MPIfR 6-cm Strong Source Surveys S4 and S5 (Pauliny-Toth et al. 1978, Kühr et al. 1981a). The selection criteria were: (a) declination (1950) > 35 deg, for good u,v-coverage with existing telescopes; (b) galactic latitude $|b| > 10$ deg; and (c) total flux density at 5 GHz $\geq$ 1.3 Jy (at the epoch of the original surveys). The flux density limit was chosen to include a moderately large number of sources strong enough to be mapped with the Mark-II system.

The sample thus defined contains 20 classical double radio sources and 45 core-dominated sources (having > 95% of their flux density arising in a region smaller than about 1 arcsec). Most of the classical double sources were known from VLA and other observations to contain no compact component strong enough to map with current Mark-II VLB systems (i.e., > 0.25 Jy). All 65 sources are listed in Table 1, which gives the source names, optical type (galaxy, quasar, BL Lac object, or empty field), redshift where available, and large scale radio structure (I or II indicates a classical double source of Fanaroff-Riley class I or II; U indicates a core-dominated or unresolved source); the remaining columns of Table 1 will be explained below.

3. OBSERVATIONS

We made observations in three stages. All the observations were made at 5 GHz. First, we made brief ("snapshot") observations to determine which sources in the complete sample could be adequately mapped. A detection is indicated by "Y" in the column headed "VLB?" in Table 1. Then we made first-epoch maps of the sources detected in the finding survey from full-track (10-11 hour) observations with three or four antennas of the U.S. VLBI Network together with the 100-m antenna of the MPIfR at Effelsberg (in most cases). The observations were completed in seven sessions scheduled by the U.S. VLBI Network between 1978 and 1982, as indicated in Table 1, in which the antennas used are shown by their conventional abbreviations. Finally, we have begun the third stage: second-epoch maps of all the sources. We shall present preliminary results of some of the second-epoch observations later in this Symposium (Readhead et al. 1984).

TABLE 1
The Complete Sample

Source		Opt	z	Radio	VLB?	--- First Epoch -- Mapped	Antennas	-- Second Epoch -- Mapped	Antennas	Classification
0016+731		Q	-	U	Y	1982 Apr	BKGFO			Very compact
0040+517	3C20	G	0.350	II	N	----				----
0108+388	OC314	EF	-	U	Y	1979 Jul	GFOH	1982 Dec	BKGFO	Double
0133+476	OC457	Q	0.86?	U	Y	1978 Dec	GFOH			Compact
0153+744		Q	-	U	Y	1982 Apr	B GFO			Double
0210+860	3C61.1	Q	0.184	II	N	----				----
0212+735		BL?	-	U	Y	1980 Sep	BK FO			Asymmetric
0220+427	3C66B	G	0.0215	I	N	----				----
0314+416	3C83.1B	G	0.0181	I	N	----				----
0316+413	3C84	G	0.0172	U	Y	1978 Dec	GFOH			Unclassified
0404+768	4C76.03	G	-	U	N	----				----
0454+844		BL	-	U	Y	1981 Aug	BKGFO			Compact
0538+498	3C147	Q	0.545	U	Y	(see Simon et al.)				Steep-spect
0605+480	3C153	G	0.2769	II	N	----				----
0710+439	OI417	G	-	U	Y	1980 Jul	BKGFO	1982 Dec	BKGFO	Double
0711+356	OI318	Q	1.620	U	Y	1980 Jul	BKGFO	1982 Dec	BKGFO	Double
0723+679	3C179	Q	0.846	II	Y	(see Porcas et al.)				Central cmpt
0804+499	OJ508	Q?	-	U	Y	1979 Dec	BKGFO			Very compact
0809+483	3C196	Q	0.871	II	N	----				----
0814+425	OJ425	Q	-	U	Y	1979 Jul	GFOH			Compact
0831+557	4C55.16	G	0.2420	U	Y	1979 Dec	KGFO			Steep-spect
0836+710	4C71.07	Q	2.17	U	Y	1980 Sep	BK FO			Asymmetric
0850+581	4C58.17	Q	1.322	U	Y	1980 Jul	BK FO			Unclassified
0859+470	4C47.29	Q	1.462	U	Y	1978 Dec	GFOH			Compact
0906+430	3C216	Q	0.670	U	Y	1979 Dec	BKGFO			Steep-spect
0917+458	3C219	G	0.1744	II	N	----				----
0923+392	4C39.25	Q	0.699	U	Y	1978 Dec	GFOH			Unclassified
0945+408	4C40.24	Q	1.252	U	Y	1979 Jul	GFOH			Steep-spect
0951+699	M82	G	0.0009	?	N	----				----
0954+556	4C55.17	Q	0.909	U	Y	----				Unclassified
0954+658		BL?	-	U	Y	----				Unclassified
1003+351	3C236	G	0.0989	II	Y	(see Schilizzi et al.)				Central cmpt
1031+567	OL553	G?	-	U	Y	----				Unclassified
1157+732	3C268.1	G	-	II	N	----				----
1254+476	3C280	G	0.994	II	N	----				----
1358+624	4C62.22	G	-	U	Y	----				Unclassified
1409+524	3C295	G	0.4614	II	N	----				----
1458+718	3C309.1	Q	0.905	U	Y	1981 Aug	BKGFO	1982 Dec	BKGFO	Steep-spect
1609+660	3C330	G	0.549	II	N	----				----
1624+416	4C41.32	G?	-	U	Y	1980 Jul	BKGFO			Asymmetric
1633+382	4C38.41	Q	1.814	U	Y	1979 Apr	BKGFO			Asymmetric
1634+628	3C343	Q•	0.988	U	N	----				----
1637+574	OS562	Q	0.745	U	Y	1979 Jul	GFOH			Compact
1641+399	3C345	Q	0.595	U	Y	(see Cohen et al.)				Asymmetric
1642+690	4C69.21	Q	-	U	Y	1980 Jul	BKGFO			Asymmetric
1652+398	4C39.49	BL	0.0337	U	Y	1980 Jul	BKGFO			Unclassified
1739+522	4C51.37	Q	1.375	U	Y	1982 Apr	B GFO			Very compact
1749+701		BL	-	U	Y	1982 Apr	BKGFO			Asymmetric
1803+784		BL?	-	U	Y	1982 Apr	BKGFO			Asymmetric
1807+698	3C371	G	0.05	U	Y	1978 Dec	GFOH	1982 Dec	BKGFO	Asymmetric
1823+568	4C56.27	BL?	-	U	Y	1979 Dec	BKGFO			Asymmetric
1828+487	3C380	Q	0.692	U	Y	1978 Dec	GFOH			Steep-spect
1842+455	3C388	G	0.0908	II	N	----				----
1845+797	3C390.3	G	0.0569	II	Y	1982 Apr	BKGFO			Central cmpt
1928+738	4C73.18	Q	0.36	U	Y	1980 Sep	BK FO			Asymmetric
1939+605	3C401	G	0.201	II	N	----				----
1954+513	OV591	Q	1.230	U	Y	1979 Jul	GFOH			Compact
2021+614	OW637	G	0.2266	U	Y	1979 Dec	KGFO	1982 Dec	BKGFO	Double
2153+377	3C438	G	0.292	II	N	----				----
2200+420	BL Lac	BL	0.07	U	Y	1978 Dec	GFOH			Asymmetric
2229+391	3C449	G	0.171	I	N	----				----
2243+394	3C452	G	0.0811	II	N	----				----
2342+821		EF	-	U	N	----				----
2351+456	4C45.51	G	-	U	Y	1980 Jul	BKGFO			Asymmetric
2352+495	OZ488	G	0.237	U	Y	1979 Dec	BKGFO			Double

Space allows us to present only a few of the maps here. They have a resolution of about 1 mas (or 2 mas when Effelsberg was not available). The dynamic range of the maps has improved considerably since we presented the first results from this program (Pearson and Readhead 1981): we can now usually achieve a dynamic range of between 100:1 and 200:1. The improvement over earlier results (which had a dynamic range of about 20:1) is due primarily to the use of an amplitude self-calibration scheme (based on CORTEL by Cornwell and Wilkinson 1981). Even so, the reader should be aware that the quality of the maps varies considerably from source to source, depending on the exact u,v-coverage, the source structure, and the accuracy of the calibration. The field of view of the maps is limited: we are likely to have missed weak components more than about 25 mas from the brightness peak, and the arrays are insensitive to structure on a scale larger than about 10 mas.

4. RESULTS

In the initial finding survey, we detected 45 of the 65 sources. Of the 20 undetected sources, 17 are classical double sources with central components weaker than 0.25 Jy, and the other three are supposedly "compact" sources (these should be studied at intermediate resolutions ~ 10-100 mas).

We have made first-epoch maps of 37 of the 45 detected sources. The remainder include four sources which have been extensively studied by other people (3C147, 3C179, 3C236, and 3C345, all described in other contributions to this Symposium), and four which were too weak for satisfactory mapping with Mark-II; we hope to map these later with Mark-III.

The sample of 45 detected sources includes 30 quasars or BL Lac objects, 14 galaxies, and one empty field. Unfortunately, only 27 have measured redshifts. The redshifts range from 0.05 for the galaxy 3C371 to over 2 for some of the quasars. There is a correspondingly wide range in the linear scales and luminosities of the sources.

5. CLASSIFICATION

In order to impose some order on the diversity of structures found in the VLBI maps, we have attempted to separate the sources into a number of groups with similar characteristics, based on the VLBI maps, the radio spectra (obtained from the literature, primarily Kühr et al. 1981b), and the radio variability of the sources (monitored at 10.8 GHz by Seielstad et al. 1983). The classification is necessarily somewhat subjective and provisional, as there appears to be a wide range of source types, with several sources showing characteristics of two or more of the groups. Further observations may either clarify our classification or show that the attempt is misguided. Essentially, we have chosen a number of well-studied, "archetypal" sources, and looked for similar characteristics amongst the others. Our assignment of sources to classes is indicated in Table 1 and summarized in Table 2. We have not attempted to classify eight of the sources in the sample: four (0316+413 = 3C84, 0850+581, 0923+392 = 4C39.25, and 1652+398) do not clearly belong in any of the classes we have described, and the remainder are the four sources which we were unable to map with Mark-II. We shall now discuss each class in turn.

TABLE 2 - Classification

Central components of classical double sources:	3
Steep-spectrum compact sources:	6
Very compact sources:	9
Asymmetric sources ("core-jets"):	13
"Compact double" sources:	6
Unclassified:	8
	--
Total:	45

6. CENTRAL COMPONENTS OF CLASSICAL DOUBLE SOURCES

This class is very easy to identify. We detected central components in three of the 20 sources in the complete sample which are dominated by extended emission. The results are clearly biased towards sources with unusually strong central components. Two of the three sources (3C179 and 3C236) will be discussed by other participants in this Symposium; the third is 3C390.3 which has also been mapped by Preuss et al. (1980) and Linfield (1981). All three sources show good alignment between the nuclear structure and the outer lobes. One (3C179) is definitely superluminal (Porcas 1981), and one (3C390.3) is apparently not ($v/c < 0.5$: Preuss et al.). It is of interest that 3C390.3 shows evidence for two-sided ejection: Linfield's 10.7-GHz map shows a "core-jet" structure directed towards the bright, compact SE lobe, while both our 5-GHz map and that of Preuss et al. show another component 5 mas away on the NW side of the "core".

7. STEEP-SPECTRUM COMPACT SOURCES

This class of source is the subject of several contributions to this Symposium. The sources are characterized by a steep, straight spectrum, usually with a low-frequency turnover near 100 MHz, and sometimes flattening at high frequencies. They show structure on all angular scales from 1 mas to 1 arcsec. The VLBI maps of three of these sources are shown in Figure 1, together with VLA maps (Pearson, Perley, and Readhead, in preparation). The VLBI structure is complex, showing a compact, flat-spectrum core, and in some cases a central "jet" which may be misaligned by as much as 90 deg from the large-scale structure. All the sources, except 0831+557 which has a peculiar structure, are

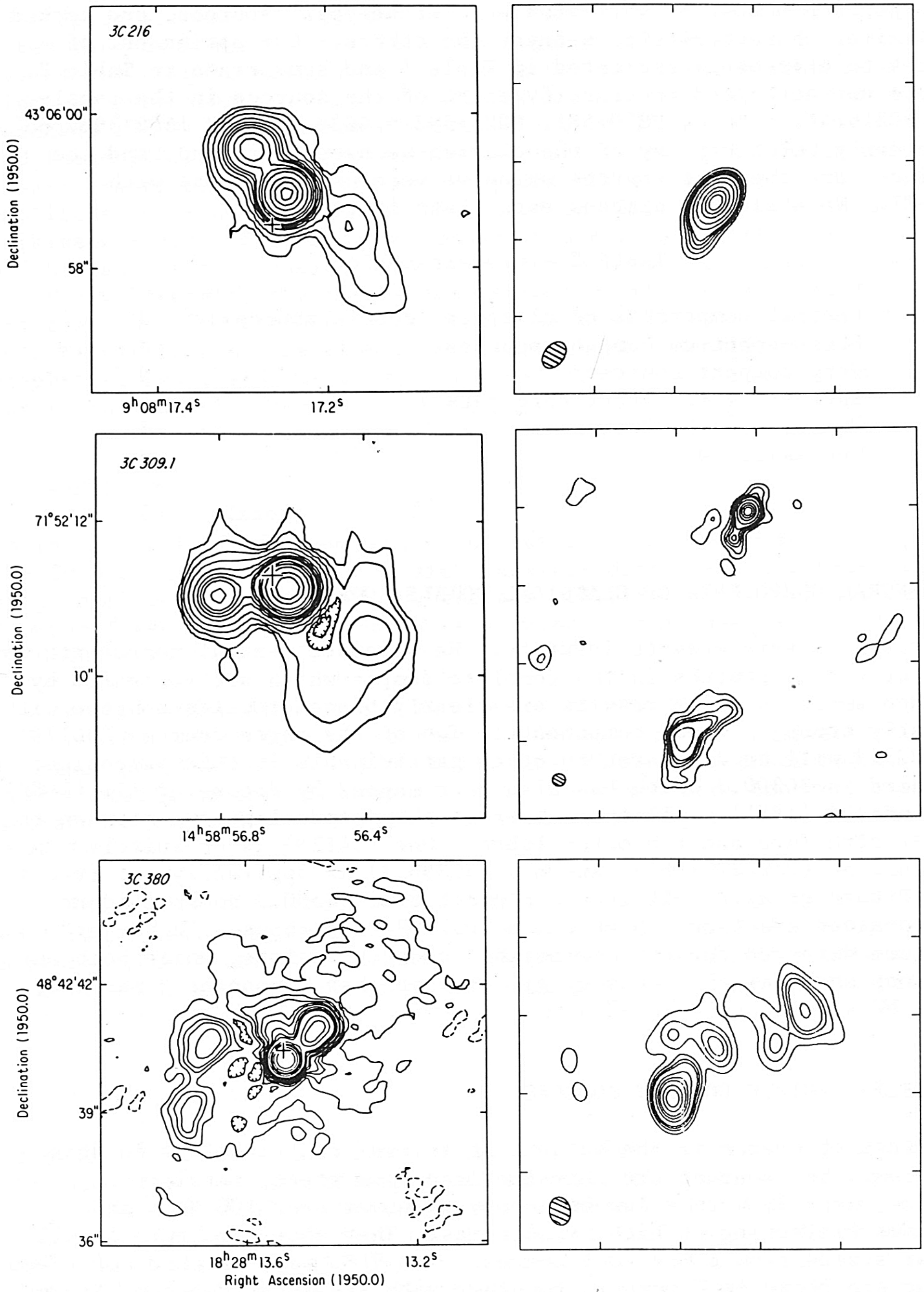

Fig. 1. 5 GHz VLA maps (left) and VLBI survey maps (right) of three "steep-spectrum compact" sources. The VLBI map of 3C216 is 20 mas square; the VLBI maps of 3C309.1 and 3C380 are 40 mas square.

quasars. These sources can perhaps be understood as normal extended double sources seen "end-on", but if this is the case, then relativistic beaming is required to account for the large number of these sources in the sample. There is some evidence from inverse-Compton arguments that relativistic bulk motion is occurring in two of these sources (3C147 and 3C390.3; Simon 1982).

8. VERY COMPACT SOURCES

A number of the sources were only barely resolved in our observations; for example, in 0016+731, 0804+499, and 1739+522, the visibility is > 95% even on transatlantic baselines. All the sources in this class are highly variable, changing by 50% or more in 4 yr or less (at 10.8 GHz). All are fairly strongly polarized (> 1%) and all are quasars or BL Lac objects. The hybrid maps show some evidence for low-brightness structure at a level of < 1% of the peak.

9. ASYMMETRIC SOURCES

A large number of the sources appear to be asymmetric sources like 3C345. The term "core-jet" is frequently used to describe these sources, although in only a few is there sufficient evidence to justify the word "jet". They are characterized by a strong, compact component at one end of a lower-brightness linear feature. When observations at a second frequency are available, the core is found to have a flat (self-absorbed) spectrum while the jet has a steeper, transparent spectrum. Two examples are shown in Figure 2. All these sources are variable, though not as violently so as the very compact sources. Two of the sources in this class are known to be superluminal (3C345 and BL Lac) and others may very possibly be (e.g., 3C371: Readhead _et al_. 1984). In some cases the VLBI structure is well aligned with outer arcsecond-scale structure (e.g., 3C371, 1642+690). Lack of alignment does not imply that there is no connection, however, as 3C345 illustrates (Browne _et al_. 1982).

10. COMPACT DOUBLE SOURCES

The existence of a distinct class of symmetric, compact double VLBI sources was first pointed out by Phillips and Mutel (1982). These objects are dominated by two components of almost equal brightness, separated by 5 - 20 mas. It turns out that several of them have additional weaker components, so the term "compact double" is a misnomer, although we shall continue to use it here. These sources appear to be distinctly different from the others in several respects: they have radio spectra with a single smooth "hump" peaking around 1 - 5 GHz, and no steep spectrum component; they have no structure on arcsecond scales brighter than 0.2% of the peak; they are only slightly variable (< 10% in 4 yr); and they have very low radio

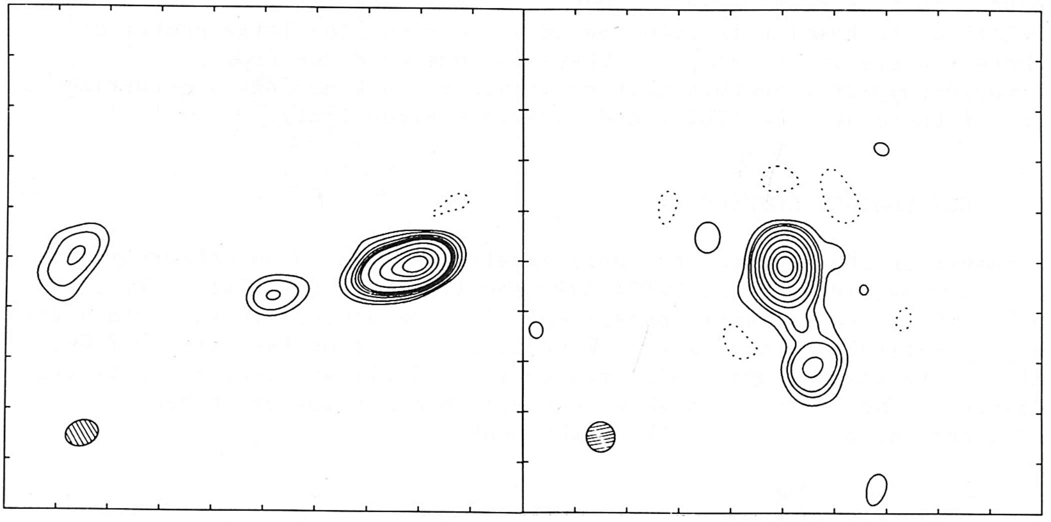

Fig. 2. 5 GHz VLBI survey maps of two "asymmetric" sources. Left: 0212+735; right: 1642+690. Both maps are 20 mas square; the restoring beams are indicated by the hatched ellipses.

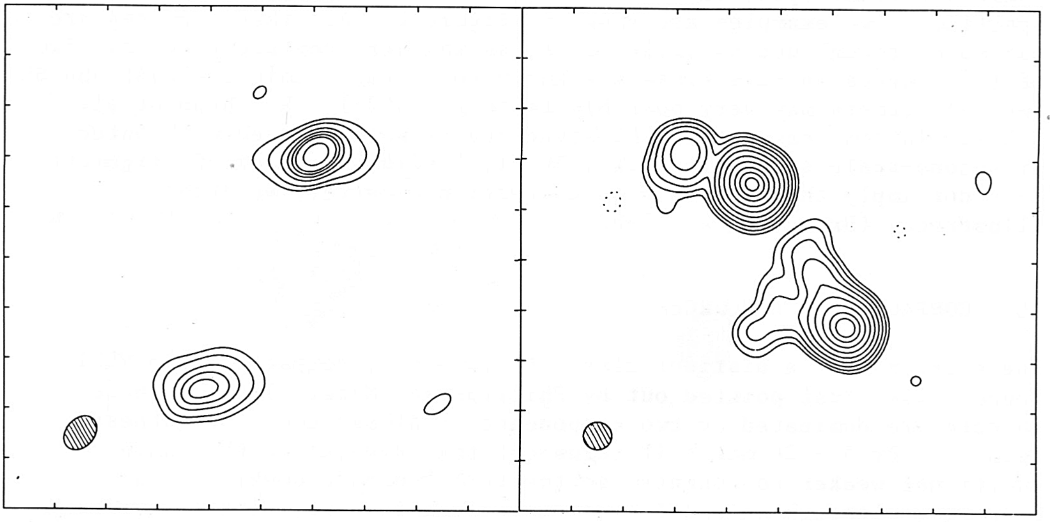

Fig. 3. 5 GHz VLBI survey maps of two "compact double" sources. Left: 0153+744; right: 2021+614. Both maps are 20 mas square; the restoring beams are indicated by the hatched ellipses.

polarization (< 0.2% in all except 0711+356). The correlation of double structure with humped spectrum was noticed in an independent sample by Phillips and Mutel (although not all sources with such spectra are compact doubles), and the correlation between humped spectrum, low variability, and low polarization was noticed by Rudnick and Jones (1982). Figure 3 shows VLBI maps of two of the sources in this class; further examples can be found in the contribution by Readhead et al. (1984). In some cases, observations at another frequency show that the sources are not as symmetric as they appear at 5 GHz, and some should perhaps be allocated to our "asymmetric" class instead (see Readhead et al. 1984). In particular 0711+356 looks out of place in the "compact double" class, and fits better into the "asymmetric" class.

11. TRENDS AND CORRELATIONS

Finally, we should like to summarize some of the trends which have already emerged from our work.

11.1. Radio spectrum

Most of the compact double sources have a distinctive "humped" spectrum. By contrast, most of the compact and very asymmetric sources have a flat or complex spectrum over a wide frequency range. Unfortunately, variability may corrupt the published spectra, and more single-epoch spectral measurements (like those of Owen et al. 1980) are needed to see if there is a real difference in spectrum between the classes.

11.2. Large-scale radio structure

A considerable body of information on the arcsec-scale structure of the sources is available from work with the VLA by Perley (1982). It is notable that none of the six "compact doubles" has any extended structure, while several of the very compact and asymmetric sources do (as do all the steep-spectrum compact sources). Of the seven asymmetric sources with large-scale structure, only three show a good agreement between mas and arcsec position angle, presumably owing to curvature in the sources.

11.3. Radio polarization

Perley (1982) and Rudnick and Jones (1982, 1983) have measured the integrated polarization of most of the sources at 5 GHz. The compact double sources all have low polarization (< 0.5%), while the very compact and asymmetric sources usually have high polarization (1 - 8%). Asymmetric sources generally have higher polarization than the very compact sources. There is no clear correlation of polarization position angle with structural position angle, perhaps because the former is corrupted by Faraday rotation.

11.4. Optical identification and spectrum

The optical data on the objects are very inhomogeneous, and in particular, there has been no systematic attempt to distinguish between quasars and BL Lac objects. We have begun a program to obtain high-quality spectra of all the objects using the Palomar 5-m telescope, which we hope will improve the situation. But with such information as is available, we can again see a difference between the compact double sources and the others: while only 12 of the 45 VLBI sources are identified with galaxies, three of the six compact double sources are galaxies (and thus fairly low-redshift objects).

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